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Interaction through touch and manipulation is known as haptic interaction. We are working to develop advanced haptic technology that allows human users to touch, feel, grasp, and manipulate a set of special objects: objects located remotely, objects too small, too large, or too dangerous for normal human interaction, or objects that exist only in simulated worlds (virtual objects). We have built a baseline haptic system that includes a light, high bandwidth force feedback device that allows the user to touch and manipulate virtual objects in a simulated environment. We have created software that simulates the behavior of and interaction between virtual objects. We have designed efficient contact detection software for detecting the collision between simulated bodies or the collision between those bodies and the haptic interface. We have created haptic algorithms for mediating the force that the user feels when touching a virtual object. Using these components we have created a collection of working demonstrations to illustrate the functionality of an advanced haptic system. Finally, we have built prototype, integrated haptic demonstrations for aircraft maintenance training and a common surgical procedure known as an anastomosis.

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Marc Raibert NHC 5/17/96

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Look and Feel:
Haptic Interaction for Biomedicine

1995 Annual Report

1 Introduction

People use their hands to touch, manipulate, and learn about the world around them. Interaction through touch and manipulation is known as haptic interaction. Rather than study how humans achieve their remarkable skill at haptic interaction, we are working to build machines that amplify, enhance, and transport these human skills. We are working to develop advanced haptic technology that allows human users to touch, feel, grasp, and manipulate a set of special objects: objects located remotely, objects too small, too large, or too dangerous for normal human interaction, or objects that exist only in simulated worlds (virtual objects).

Advanced haptic interaction will have a wide range of applications in biomedical, military, and civilian areas. It will allow design engineers to "pick up" new designs, "try them out," and see how they will behave, before they ever leave the drawing board. Engineers will sculpt the shapes of new parts in the computer, as though made of clay. Remote experts will aid the local novice in performing delicate procedures. Medical students will train by manipulating virtual organs, without risk to human patients or animals. Students will probe any part of the virtual patient with impunity and view a wide range of conditions from any vantage point. This work will enable applications ranging from familiarization and training in domains requiring hand/eye skills (surgery, mechanics, maintenance, for example) to the enhancement of operations in remote, scaled, unfamiliar, and hazardous environments.

Systems for computer haptic interaction need to have three parts: a part that mechanically interfaces to the user's hand (and/or arm), a part that mediates the interaction between the hand and virtual or remotely located objects, and a part that simulates how the objects will behave when touched. These components are force feedback devices, haptic algorithms, and physics-based simulation, respectively. In support of the surgical simulator and other related projects we are building a series of advanced haptic systems that consist of a mechanical haptic interface device, a real-time computing system, a dynamic simulation system, and computer graphics. The systems we build provide an entirely new way for people to interact with remote and virtual objects (Fig. 1). This report describes our progress in developing advanced haptic systems. It describes basic technology and methods we have developed as well as the application of the technology to biomedical haptics.

The immediate goal of our effort in biomedical haptics is the development of a virtual surgery simulator that will allow the user to practice an anastomosis (Fig. 2), a common surgical

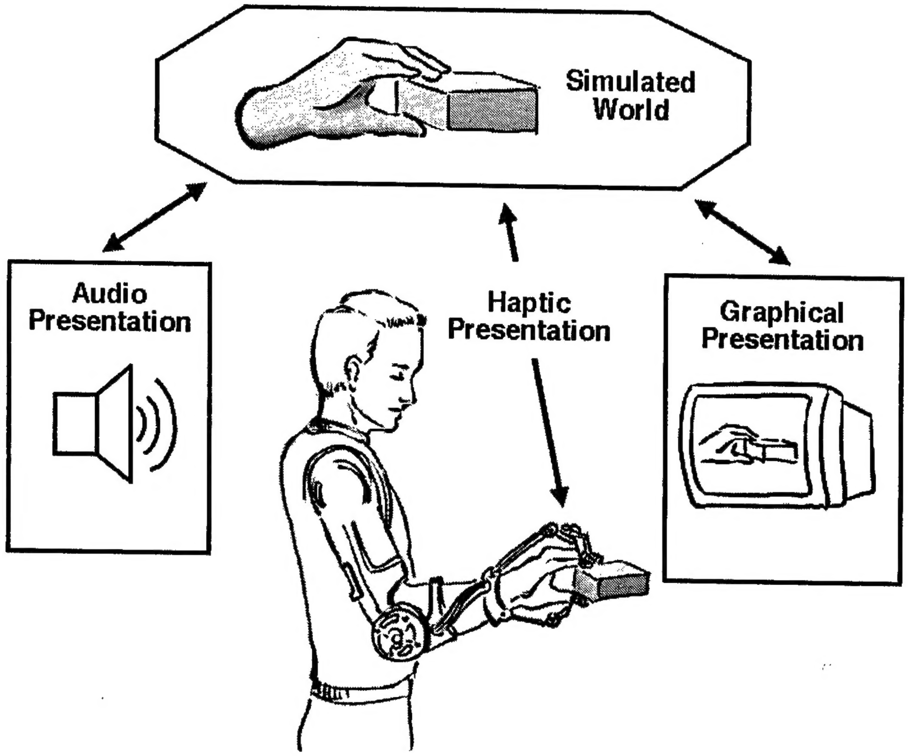


Figure 1: Haptic, Graphic, and Audio Presentation of a Virtual Object

procedure that involves suturing two tubes together using standard surgical tools. A long term goal of this effort is to provide a setting in which medical students and surgeons can practice a variety of surgical procedures under conditions that are better for learning than a live operating room. Progress in surgical simulation will also contribute to the field of teleoperation.

2 Progress on Components of an Advanced Haptic System

The primary components of any advanced haptic system will include high fidelity haptic interfaces, haptic algorithms and dynamic simulation. In Table 1 we summarize our progress on a list of development tasks for advanced haptic systems including the virtual surgical simulator.

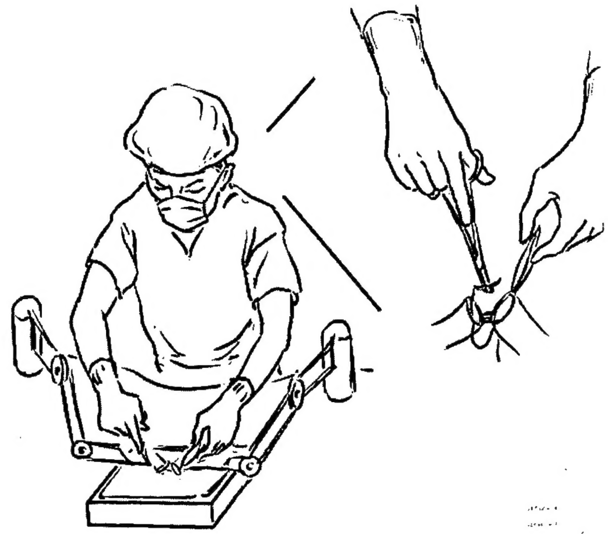
Next we detail our progress in these areas.

2.1 Advanced Haptic Interface Devices

The Phantom (Fig. 3) haptic device is a light weight, high bandwidth mechanical interface that allows the user to touch and manipulate a virtual or remotely located object. Haptic fidelity and high resolution are important for conveying a detailed sense of touch and are thus emphasized over kinematic complexity and high force capacity. High fidelity and resolution are obtained by maximizing bandwidth through the design of stiff, lightweight, and low friction structures

- *Advanced Haptic Interface Devices:* The haptic device is the mechanical interface that allows the user to touch and manipulate a virtual or remotely located object.
  - Phantom haptic device interfaced to SGI and PC
  - Instrumented medical tool attachments
    * debakey forceps
    * needle holder
  - Virtual medical tools
    * debakey forceps
    * needle and needle holder
    * scalpel with scalpel holder
    * hemostatic forceps
    * intestinal forceps
    * dissecting forceps
    * scissors
    * retractor
  - Instrumented gimbal measures tool position and orientation
  - Powered, two finger attachment designed and tested (MIT Task)
- *Haptic Algorithms:* The haptic algorithms mediate the forces the user feels with the Haptic Interface Device.
  - Two handed interaction demonstrated
  - Two finger manipulation demonstrated
  - Rigid body contact force models
  - Flexible body contact force models
  - Coulomb friction
  - Haptic textures
- *Physics-Based Simulation:* Real-time physics-based simulation is used to calculate the behavior of objects, interactions among objects, and interactions between objects and the user
  - Automatic simulation generation for rigid body systems
  - Loadable object shapes from CAD files
  - Programmable bulk properties of simulated objects
  - Compliant flexible skin
  - Compliant flexible tubes
  - Contact detection between polygonal shapes
  - Contact detection between point and flexible tubes
  - Contact detection between point and terrain
  - Surgical needle interaction with flexible tissue
  - Texture mapped graphics

Table 1: Progress List for Advanced Haptic System Development



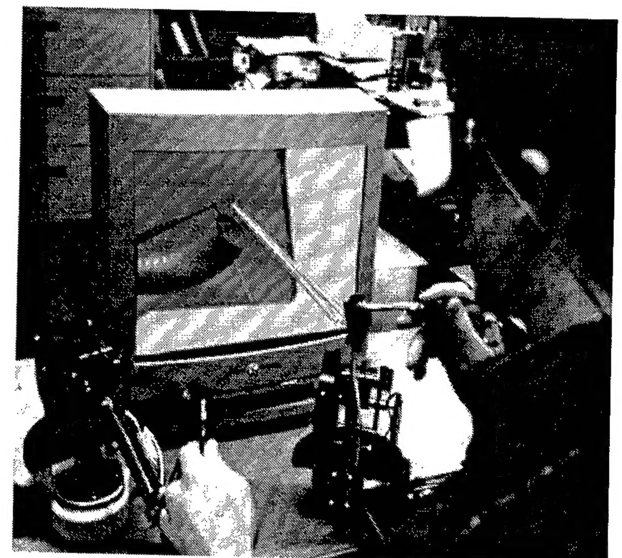


Figure 2: The Virtual Anastomosis Simulator: an artists conception and a working prototype at BDI.

and transmissions. The Phantom is interfaced to both a PC and an SGI graphics workstation. Haptic algorithms and object simulation code are run on the PC while the graphics workstation is used for 3D visual display.

The position of the tip of the Phantom is measured using encoders. The phantom can apply forces back to the user along the three translational axes. The three gimbal option measures the orientation of a probe or tool attached to the Phantom. Attaching instrumented medical hardware to the haptic device increases the realism of interaction by providing a familiar interface to the user. A powered, two finger device has been designed by the MIT group and tested at BDI. This device can apply a gripping torque to the user to simulate the sensation of grasping an object with two fingers. A similar concept could simulate the forces required to grasp an object with a forceps or pliers.

Further development of the haptic device is underway and will include piezo-vibration stimulators for ultra-high bandwidth sensation, multi-fingertip interaction, and large workspace.

2.2 Haptic Algorithms

The haptic algorithms mediate the force the user feels with the Haptic Interface Device. These forces may be the contact force produced by pushing or pulling a simulated object, or those from poking or plucking a flexible membrane, or they may be the forces that produce a sense

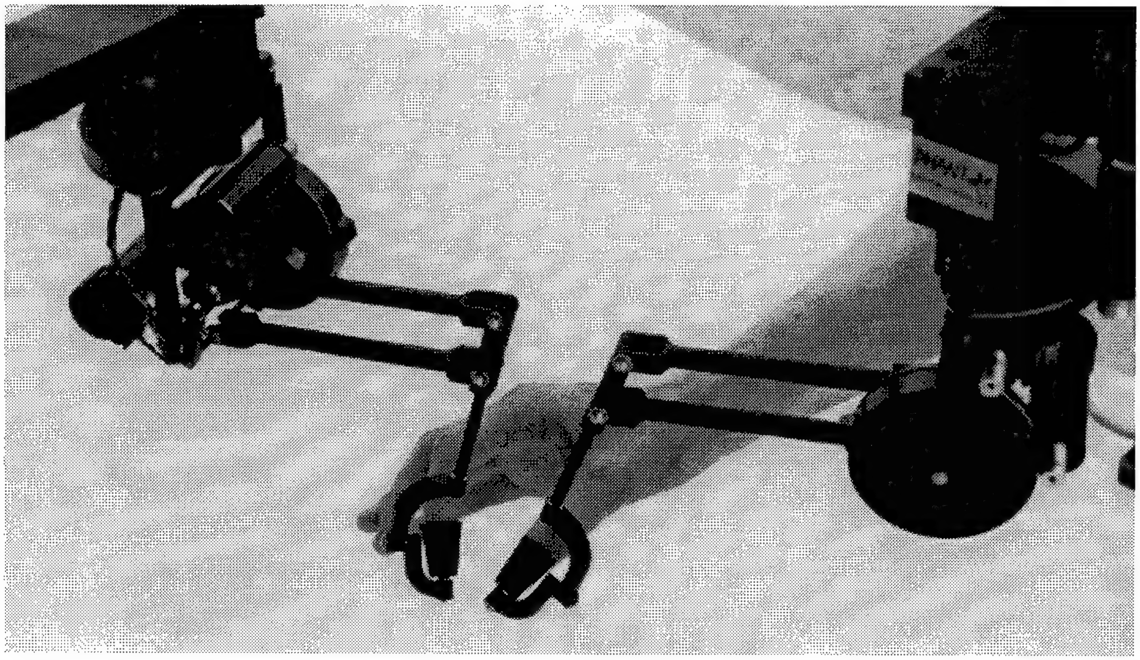


Figure 3: The Phantom Haptic Interface Device

of textured surface. The contact force models we use incorporate the material properties of the simulated objects and are dependent upon the simulated object's behavior. Texture forces are produced by spatially and temporally varying the contact forces.

2.2.1 Contact Force Models

The interaction force that is simulated when two objects touch is computed with a contact force model. The contact force is computed using models of surface compliance and friction. The contact force is also dependent upon the state of the objects in a simulation. For example, the forces required to touch a needle to flexible tissue depends upon whether or not the needle has initially penetrated the tissue. These types of contact forces depend closely upon the simulated behavior of the object. While these force models are important in lending a convincing sense of touch to an object's surface, we are developing other techniques to add richness and complexity to haptic interaction.

2.2.2 Haptic Texture Mapping

The basic goal of haptic texture mapping is to permit haptically perceivable textures to be overlaid on basic object geometry. We have experimented with creating haptic textures by making the contact forces depend upon the spatial location of the contact point. By regularly varying

the contact forces with spatial position we have created the feeling of ridges on a geometrically flat plane. Using this idea we have also created a haptic texture from a scanned in photograph by spatially correlating the contact forces with the visual image. So far the haptic textures do not work well. The best effect is achieved with a high frequency texture but we do not yet know how to generate the feel of real textured objects.

2.3 Physics-Based Simulation

Our system uses real-time physics-based simulation to calculate the behavior of objects, interactions among objects, and interactions between objects and the user. Objects can be isolated bodies, mechanical linkages, or more complicated things like tool mechanisms, deformable tissues, or organs. A basic idea of the work is that physics-based simulation allows virtual objects to move as real objects do; obeying the laws of physics, they feel like real objects when touched, and move realistically in response to touching.

The foundation of our object simulator is software that we developed in previous work that automatically creates highly-optimized dynamic simulations of things that move from simple descriptions of the objects. The physical simulations include material properties than can be changed by the user to tune the feel of the object. For example, we can change the mass of a rigid body, the compliance of its surface, or the coefficient of friction between a surface and the haptic device.

2.3.1 Rigid Body Systems

A general object loader is working that allows multiple 3D objects to be loaded, dynamically simulated, and touched or manipulated. The software includes automatic contact detection, equation generation, and 3D graphics. The shape of these objects can be defined with a CAD file that describes their surface geometry. The geometry is used for both visualization and contact detection. Bulk properties of the bodies like mass, coefficient of friction, or surface impedance can be specified by the user. The haptic tool used for manipulation in the virtual environment is a special kind of simulated object. Its position and orientation are driven by the Phantom. The forces of interaction between it and other simulated objects are computed from the haptic algorithms.

2.3.2 Flexible Tissue

To support the simulation of surgical procedures, we have expanded our simulation library to include prototype simulations of flexible tissue and flexible tubes. At BDI we are using flexible tissue simulation techniques that strive for computational simplicity and speed while

providing convincing behavior. One prototype flexible tissue simulation included a planar surface that deformed when pushed or pulled. Rigid objects with varying surface compliance could be positioned beneath the flexible tissue to simulate a palpation task. We also have simulations of whole and severed hollow tubes. The tubes move when touched and the surfaces deform when the tubes are poked or plucked. By varying the radii of the tubes with time we can simulate the look and feel of a pulsing vessel. The flexibility or surface deformation of a flexible tube can be tuned to best approximate the feel of biological material.

2.3.3 Contact Detection and Contact Force Models

An important component of object simulation is the contact detection algorithm that determines when simulated objects are colliding or when the user is touching a simulated object. The algorithms use the geometry of the simulated objects to compute the distance separating them. We have created general contact detection algorithms for computing the distance between polygonal objects. This general contact algorithm is insensitive to the number of polygons on an object. We also have written special case algorithms that are efficient for certain applications such as contact against flexible tubes or terrain like features.

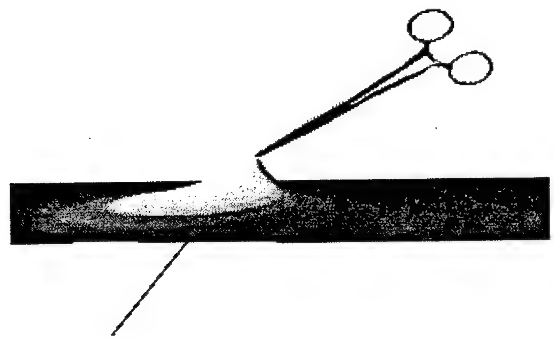
3 Haptic System Demonstrations

We are compiling a suite of haptic demonstrations for the purpose of testing, communicating, and delivering advanced haptic systems. The collection of demonstrations provides a measure of what these systems can do in existing implementations. The demonstrations rely on one or two Phantom haptic devices that are interfaced to a high performance PC that runs dynamic simulation and haptic algorithms. The PC is networked to an SGI graphics computer for 3D graphic displays. The CrystalEyes stereographic and head tracking product has been included on some demonstrations for enhanced 3D visualization. Here is a list of the demonstrations currently in operation.

- *The Friction House:* This concave piece built from convex shapes is fixed in space. Using the phantom you can feel the shape and judge the friction of its surface as you drag your finger across the surface. Forcing the graphic image of the virtual finger to lie on the surface of the house during contact improves the sensation of hardness.

- *Toy Box:* The rigid body is the starting point for 3D dynamic simulation. We can simulate the interaction between static or dynamic rigid bodies. The body shape can be loaded into the system in a standard CAD format. Convex rigid bodies or concave bodies that are comprised of convex subshapes can be touched, felt, and manipulated, bounced off the floor or walls or each other. We have built a set of these objects (a jack, a block, a barrel, and a ball) and a box with floors and walls to contain them while you poke them around. We call it the toybox.

- *Flexible Skin:* Using forceps the user can poke, stroke, or pluck a sheet of skin. The skin is compliant and deforms when touched. With a delicate touch the user can just detect lumps under the skin. With needle and needle holder, the user can practice suturing technique. At first the skin resists the needle then with just enough force the needle punctures the skin.

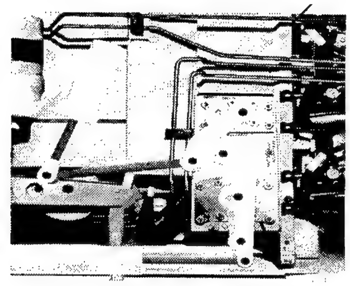


- *Flexible Tube:* Roll up the flexible tissue into a tube and you have a blood vessel, small intestine, colon, or one of many biological tubes found in the human body. The tube bends away from you when you poke it or toward you when you pluck it with the forceps. This gross deformation of the tube is accompanied by local surface deformation. The tube is a bit slippery so using two hands is recommended. Hold the tube with the debakey forceps in the left hand while puncturing it with a needle and needle holder held in the right hand. Release the needle in the tube then reach around the inside and pull it through to complete the suture. We have needles pulling thread and will soon have the virtual anastomosis, or the tying of two tubes together.

- *Haptic Textures:* We have made a first pass at displaying haptic textures. We created a haptic texture by spatially varying the contact forces. The best effect is achieved with a high frequency texture but we do not yet know how to generate the feel of real textured objects.

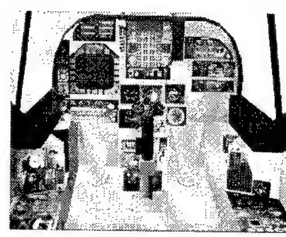
- *Hinged Domino:* One step more complicated than the rigid body, the hinged domino features two rigid bodies hinged together. They can fold closed like a book or open end-to-end to make a tower. Friction between the ground and the dominoes make it possible to stand the tower up on end with only your finger tip. Texture maps applied to the dominoes improve the visual realism. A dynamic simulation of the hinge mechanical structure makes it feel like a real articulated object when touched.

- *Linkage:* Yet more dynamically complex is the Vernier Non-Linear Nosewheel Steering Linkage. This is a dynamic simulation of a four bar linkage used in the steering mechanism of the AV8B Jet Aircraft (The Harrier). Four bar linkages can have a wide variety of behavior depending on their configuration. Manipulating the linkage is the easiest way to begin to understand its behavior. Tighten the friction nut and feel the resistance of the linkage increase.



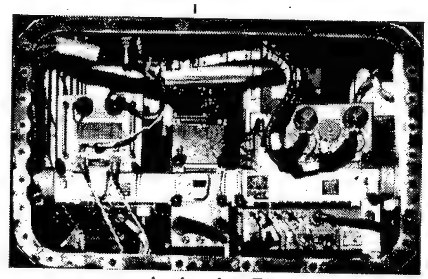
NoseWheel Linkage

- *Cockpit:* Static objects, one degree of freedom dynamic objects, texture maps for realistic visuals, and sounds recorded from real aircraft trainers make up the simulated cockpit of the AV8B. By pushing buttons, turning dials, throwing toggle switches, and reading lighting system displays, the user plays the role of a maintenance technician setting up and diagnosing a radar system test.



Cockpit

- *Avionics Bay:* A continuation of the radar test started in the cockpit. Here the technician can feel avionics components in a rear bay of the aircraft. Using a voltage probe the user can measure the voltage on an electrical connector. Here, feeling the pins is crucial to keeping the voltage probe in place.



Avionics Bay

4 Two Handed Anastomosis

As a means of pulling together the basic technology required for biomedical haptics, we are working on a focused application, a two handed anastomosis. The anastomosis is a common surgical procedure that involves suturing together two blood vessels, esophagus, colon, or other biological tubes. The dominant features of the anastomosis that our simulator currently supports

are the use of common surgical tools to manipulate and grasp compliant, deformable tubes, grasp and release suturing needles and insert and remove suturing needles from flexible tubes. In continuing work on this project we will add suture material to the needle so that we may begin tying two tubes together.

We have constructed a Virtual Surgery Station that allows the surgeon and surgical subject to be in the correct relative proximity to one another. The user stands with hands at table height holding a debakey forceps in the left hand and a needle holder in the right hand, each mounted to a Phantom Device. Looking down at his hands, the surgeon instead sees a mirror reflecting the computer graphic image of the subject and the virtual tools. This image is produced in approximately the correct location by using an SGI monitor mounted overhead. A hand rest allows the surgeon to stabilize his hands for delicate manipulation. We have demonstrated this Virtual Surgery Station to Surgeons at the Pennsylvania State's Hershey Medical Center. They plan to incorporate it into their Virtual Training Hospital.

5 Commercialization and Related Work

BDI is developing and selling products that are closely related to the ARPA funded work. Included in the Appendix of this report are several one page fliers describing our haptic system products.

- BDI is marketing Tangible Reality(TM), a turn-key virtual environment system that includes visual images, sound, and touch. The system consists of a force-feedback device, a real-time simulation computer, a physics-based simulation environment, simulated objects, real-time 3D computer graphics, real-time 3D sound effects, and networking. Early versions of the product will support standard sets of physics-based simulated objects. Later versions will support user-defined objects and deformable objects. This product provides an initial channel for commercialization of results from the proposed research. For example "palpating in" and "haptic texture mapping" are obvious candidates for enhancing the product as we understand and develop them.
- We are selling a special version of Tangible Reality designed for training surgical procedures. The first version of the system will support two-handed anastomosis at several scales. Thomas M. Krummel, M.D., Chair of the Department of Surgery at Penn State's Hershey Medical Center is building "The Virtual Hospital." The VR Anastomosis Simulator is a key feature in his concept for reducing the cost and improving the quality of medical teaching.
- We are working with Digital Media Associates to combine haptic displays with their unique 3D display system for medical applications.

- Musculo Graphics. We have developed a joint project with Musculo Graphics Inc. to develop a trainer for wound debridement for the U.S. Army at Fort Bragg. Initial phases of this project involve development of a leg and leg wound simulator with haptic tool interaction for training. BDI will provide the haptic components of this project. A version of this simulator is included in the FY97 P.O.M.
- Nissho Electronics Corp. is a Japanese distributor of the BDI Tangible Reality System.
- VR Maintenance Trainer for the Joint Advanced Strike Technology Program. This was a program to demonstrate the applicability of VR technology to aircraft maintenance training. This project significantly leveraged our ARPA-funded project and offers other military applications.

6 Conclusions

One year into this project we have demonstrated the feasibility of many basic components of an advanced haptic system. We built a baseline haptic system for simulating and interacting with static and dynamic rigid bodies, dynamic multi-rigid body systems, bodies with loadable CAD shapes, and basic deformable tissues. We have created a collection of demonstrations to illustrate the working components of an advanced haptic system. We have built integrated haptic demonstrations for aircraft maintenance training and a surgical anastomosis. While the technical challenges to producing a complete advanced haptic system are considerable,we have not yet discovered any insurmountable problems. Never-the-less, the results of our first year's effort will help to focus our effort on the continuing project goals.

The complexity of our demonstrations are frequently limited by our computational resources. Our contact detection software is under continual refinement in order to improve efficiency so that we may experiment with ever more complicated and realistic environments. We have designed optimized software for contact detection in specialized environments such as those containing convex polygons or flexible tubes. We need to expand our suite of fast contact detection techniques for additional specialized environments and/or create efficient contact detection software for more general environments. Our experiments with haptic textures were not completely successful. We have not yet been able to produce a convincing sense of touch against a textured surface. However, our effort in this regard has been limited. We have ideas we have not tried and will invest additional energy into this area during the second year. Our experiments with multi-fingered haptic devices have been limited. What experimentation we have done has raised the issue of the need to provide torque feedback to the user. The problem is not just one of providing a convincing sense of touch to the user. Torque feedback may be required to create a well behaved interaction with a physically simulated world in which torques must exist. Finally,

while the economic cost of our computational platforms is not excessive, it is high enough that it still may present a barrier to many would be customers of haptic systems. In our effort to reduce the cost and complexity of the required hardware for an advanced haptic system, we will consider porting all haptic, simulation, and graphics software to a single computational platform. Such a system may have limited performance on existing machines but could provide a functional set of tools for many would be customers.

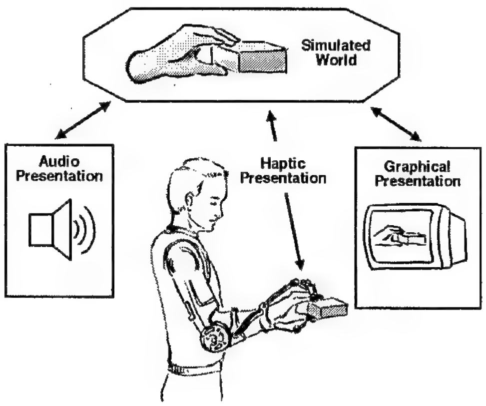
7 Appendix

Following are three one page fliers describing our haptic system products.

Tangible Reality™

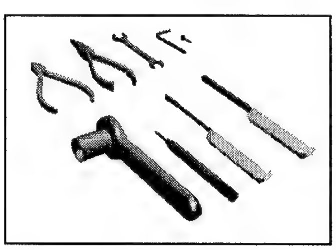
Tangible Reality Components:

- *Haptic Software Library*
- Force Feedback Device
- Haptic Real-Time Computer
- 3D Graphics and Sound



BDI Haptics Software Library:

- Kinematics for the PHANToM
- Fast contact detection
- Contact force model
- 3D object loader
- Dynamic object simulator
- Haptic textures
- Deformable tube simulator
- Virtual hand tools
- User interface
- Device drivers for WindowsNT
- Network communications
- Demonstration software



Virtual Tools

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PHANToM™ is a trademark of SensAble Devices, Inc.
WindowsNT™ is a trademark of Microsoft Corp.

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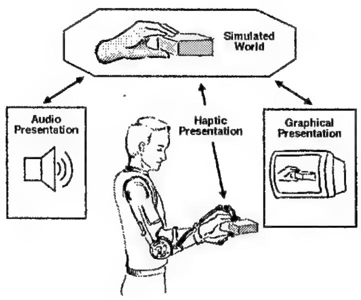
VR Aircraft Maintenance Trainer

Goal: Replace several physical trainers with virtual reality trainers

BDI

Boston Dynamics Inc. (*BDI*) and NAWC-TSD are exploring the use of virtual reality technology for JAST aircraft maintenance training. Can the diverse and expensive physical trainers currently used for 0-level maintenance training be replaced with virtual trainers? To address this question we modeled two training maintenance tasks for the AV8B within a virtual reality maintenance training environment. A videotape demonstration of this project is available from *BDI.*

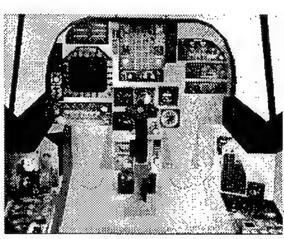


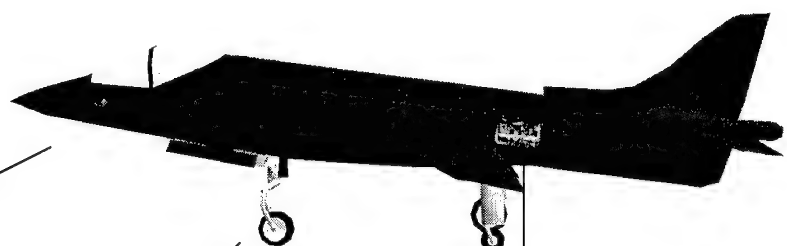
Benefits of Virtual Reality Trainers:

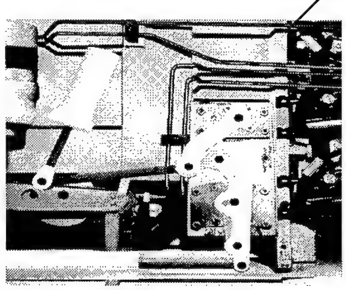
- Reduce equipment inventory
- Decrease hardware support
- Reduce space requirements
- Deployable
- Simplify logistics of training
- Improve configuration control
- Realistic training at reduced cost
- Maintenance training occurs prior to availability of aircraft
- Evaluate ergonomics of training procedures, work load, etc.
- One trainer for all aircraft

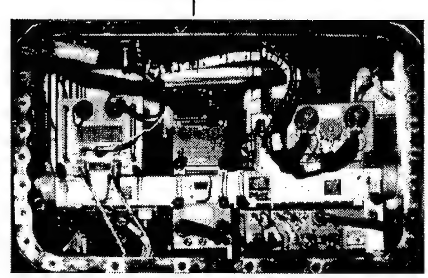
VR System Components:

- Physics-based simulation
- 3D Graphics
- Interactive haptic device
- CAD data
- Training paradigm


Cockpit


AV8B


NoseWheel Linkage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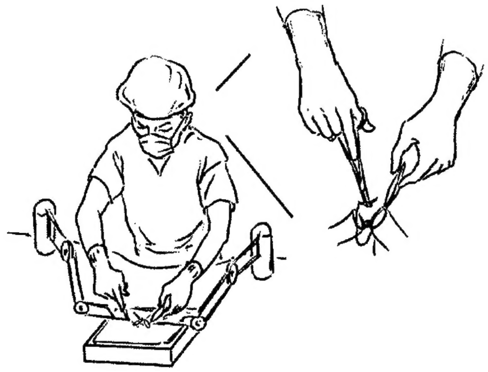
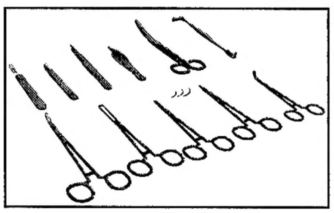
BDI

VR Anastomosis Simulation

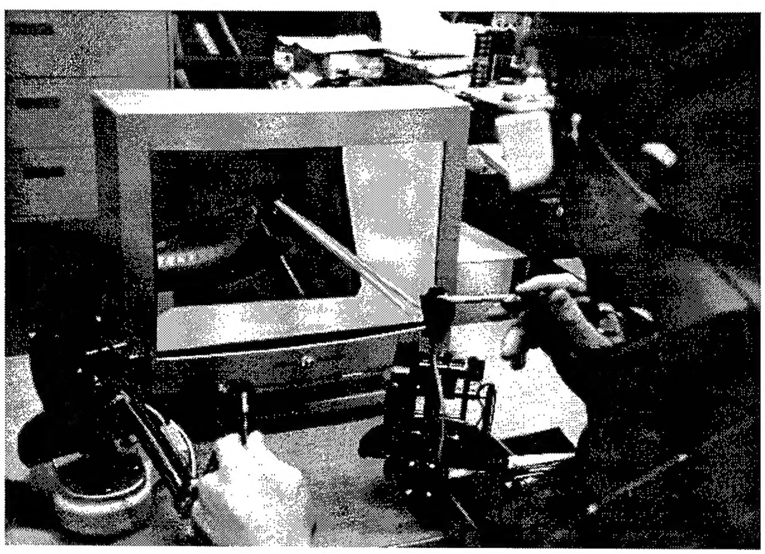


- Real-Time Force Feedback
- Physics-Based Simulation
- Flexible Parametric Tubes
- Grasping and Needle Penetration
- 3D Graphics and Sound



A surgeon's hands have a remarkable sense of touch. *BDI's* virtual reality surgical simulator is based on touch. Force feedback devices let the user feel the virtual environment in addition to seeing and hearing it. The *BDI* simulator focuses on open surgical anastomosis: the task of suturing tube-like organs. Anastomosis is ubiquitous in the operating room, and includes blood vessels, esophagus, ureters, trachea, the colon, bile ducts and other organ systems. By integrating high-fidelity force feedback devices, surgical tool interfaces, real-time 3D graphics, and physics-based simulation, *BDI* is providing an effective surgical practice space; All you need are the scrubs and mask.

The *BDI* surgical simulator is built on *Tangible Reality™*, a system consisting of force feedback devices, a real-time haptic computer, *BDI's Haptic Software Library*, and 3D graphics software. *Tangible Reality* is an integrated system that allows users to reach into virtual environments with their hands to touch, feel, grasp, and manipulate simulated objects.



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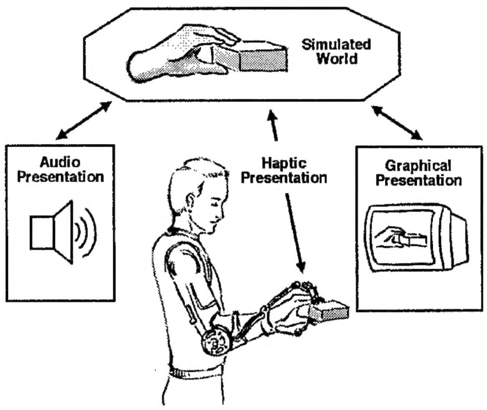
Reach in and Touch Something

Tangible Reality™

Tangible Reality Components:

- *Haptic Software Library*
- Force Feedback Device
- Haptic Real-Time Computer
- 3D Graphics and Sound



BDI Haptics Software Library:

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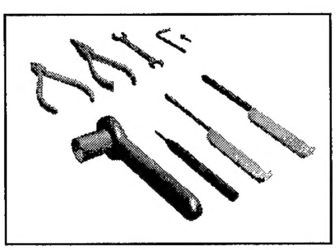

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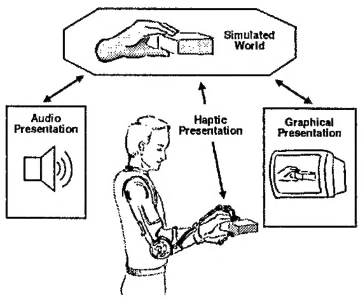

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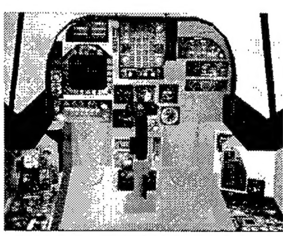

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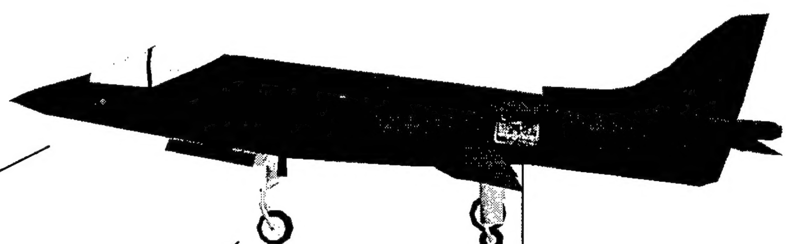

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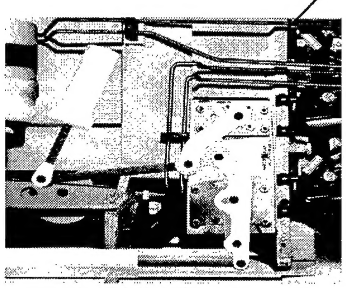

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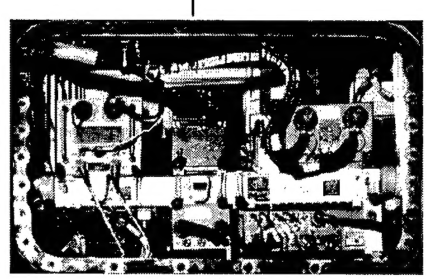

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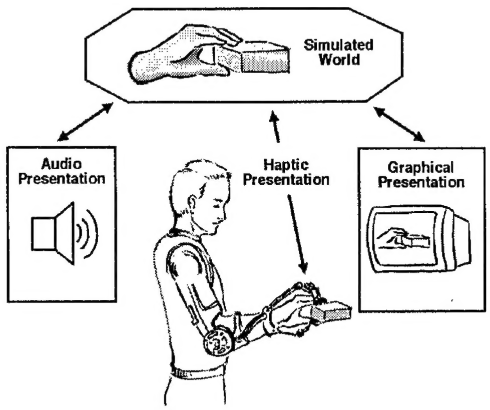

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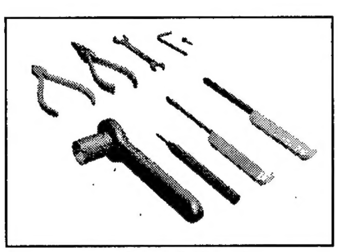

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